Optical fiber and optical transmission system

Background of the Invention

Field of the Invention

The present invention relates to a Wavelength Division Multiplexing (WDM) transmission system to perform optical transmission by multiplexing light signals having a plurality of wavelengths, and an optical fiber used as the optical transmission line for the WDM optical transmission system.

Related Background Arts

The WDM transmission system using an optical fiber network can transmit a large volume of information. The WDM transmission system comprises a transmitter to send out light signals having a plurality of wavelengths, an optical fiber to transmit these light signals, a receiver to receive these light signals, and an optical fiber amplifier to amplify these light signals. In order to increase the transmission capacity of the WDM transmission system, an attempt has been made to expand the wavelength band used for the transmission.

European Patent Application Publication No. EP 1037074 discloses an optical fiber that has appropriate chromatic dispersions in the whole range of wavelengths including 1.53 μm to 1.61 μm, in which the optical fiber amplifier can obtain a positive gain. The optical fiber can hence restrain the waveform degradation of the light signal due to a nonlinear optical

phenomenon as well as the waveform degradation of the light signal due to the accumulation of the chromatic dispersions. The zero dispersion wavelength of this optical fiber is at least 1.61 μm but not more than 1.67 μm, and the chromatic dispersion slope at wavelength of 1.55 μm is 0.15 $ps \cdot nm^{-2} \cdot km^{-1}$ or less. In the implementation examples of the cited invention, optical fibers having a chromatic dispersion slope of at least 0.07 $ps \cdot nm^{-2} \cdot km^{-1}$ but not more than 0.15 $ps \cdot nm^{-2} \cdot km^{-1}$ are disclosed.

As for the optical fibers disclosed in the above-mentioned bulletin no consideration is made about the use in 1.31 μm band and 1.45 μm band (S band).

Summary of the Invention

An object of the present invention is to provide an optical fiber which can achieve a large-volume and long-haul transmission, using light signals having a plurality of wavelengths in the wide range of wavelengths including 1.31 μm band, 1.45 μm band, 1.55 μm band and 1.58 μm band, as well as a transmission system including such an optical fiber.

In order to achieve this and other objects, an optical fiber is provided in which the chromatic dispersion is -20 $ps \cdot nm^{-1} \cdot km^{-1}$ or more but -3 $ps \cdot nm^{-1} \cdot km^{-1}$ or less in the whole wavelength range of 1300 nm to 1600 nm.

Furthermore, an optical transmission system is provided which comprises (1) a plurality of transmitters to send out light signals having wavelengths in the range of 1300 nm to 1600 nm, (2) an optical fiber to

transmit the light signals and the chromatic dispersions thereof are –20 ps·nm^{-1}·km^{-1} or more but -3 ps·nm^{-1}·km^{-1} or less at wavelengths in the range of 1300 nm to 1600 nm, and (3) receivers to receive the light signals.

An optical fiber according to an embodiment of the present invention is provided with (1) a central core region including the center of optical axis and having a first refractive index, (2) a second core region enclosing the central core region and having a second refractive index which is smaller than the first refractive index, (3) a third core region enclosing the second core region and having a third refractive index which is greater than the second refractive index, and (4) a clad region enclosing the third core region and having a fourth refractive index which is smaller than the third refractive index.

The above and further objects and novel features of the invention will be more fully clarified from the following detailed description when the same is read in connection with the accompanying drawings. It is to be expressly understood, however, that the drawings are for the purpose of illustration only and are not intended as a definition of the limits of the invention.

Brief Description of the Drawing

For convenience to understand the drawings used in the detailed description of the present invention, a brief description of each drawing is provided:

Figure 1 shows the chromatic dispersion characteristic of an optical fiber according to an embodiment of the present invention.

Figure 2 shows a preferable example of the refractive index profile of an optical fiber according to an embodiment of the present invention.

Figure 3 shows another preferable example of the refractive index profile of an optical fiber according to an embodiment of the present invention.

Figure 4 is a graph showing the chromatic dispersion characteristic of each of the optical fibers described in the implementation examples.

Figure 5 is a schematic diagram of an optical transmission system according to a first embodiment of the present invention.

Figure 6 is a schematic diagram of an optical transmission system according to a second embodiment of the present invention.

Description of the Preferred Embodiments

In the following, preferred embodiments of the present invention will be explained in detail with reference to the accompanying drawings. To facilitate the comprehension of the explanation, the same reference numerals denote the same parts, where possible, throughout the drawings, and a repeated explanation will be omitted. The dimensions in the drawing are partly exaggerated and do not always correspond to actual ratios of dimensions.

Figure 1 shows the chromatic dispersion characteristic of an optical fiber according to an embodiment of the present invention. The chromatic dispersion of the optical fiber is $-20\ ps \cdot nm^{-1} \cdot km^{-1}$ or more but $-3\ ps \cdot nm^{-1} \cdot km^{-1}$ or less in the whole wavelength range of 1300 nm to 1600 nm (wavelength band A). This wavelength band A includes the 1.31 μm band, 1.45 μm band, 1.55 μm band,

and 1.58 μm band.

A chromatic dispersion of –20 ps·nm^{-1}·km^{-1} or more enables the suppression of the waveform degradation of the light signal caused by the accumulation of the chromatic dispersions to a level not exceeding the level in the case of using a single mode fiber stipulated in G.654 of ITU at a wavelength of 1550 nm. A chromatic dispersion of –3 ps·nm^{-1}·km^{-1} or less can restrain the waveform degradation of the light signal due to nonlinear optical phenomena. Therefore, using this optical fiber as an optical transmission line can achieve large-volume and long-haul transmission with the light signal at a plurality of wavelengths within the wavelength band A.

Preferably, the chromatic dispersion of an optical fiber according to the present invention is –12 ps·nm^{-1}·km^{-1} or more but –4 ps·nm^{-1}·km^{-1} or less at all wavelengths in the wavelength band A. A chromatic dispersion of –12 ps·nm^{-1}·km^{-1} or more can more effectively suppress the waveform degradation of the light signal caused by the accumulation of the chromatic dispersions; a chromatic dispersion of –4 ps·nm^{-1}·km^{-1} or less more effectively restrains the waveform degradation of the light signal caused by the nonlinear optical phenomena. Accordingly, larger-volume and longer-distance transmission is possible in this case, using the light signals having numerous wavelengths in the wavelength band A.

More preferably, the chromatic dispersion of an optical fiber according to the present invention is –20 ps·nm^{-1}·km^{-1} or more but –3 ps·nm^{-1}·km^{-1} or less in the whole range of wavelength band of 1250 nm to 1650 nm (wavelength

band B), which is wider than the above-mentioned wavelength band A. In this case, a further larger volume and long distance transmission is possible using the light signals having numerous wavelengths in the wavelength band B which is wider than the wavelength band A.

Yet more preferably, the chromatic dispersion of an optical fiber according to the present invention is $-16\ ps \cdot nm^{-1} \cdot km^{-1}$ or more but $-4\ ps \cdot nm^{-1} \cdot km^{-1}$ or less at all of the wavelengths in wavelength band B. A chromatic dispersion of $-16\ ps \cdot nm^{-1} \cdot km^{-1}$ or more enables to more effectively suppress the waveform degradation of the light signal caused by the accumulation of the chromatic dispersions; a chromatic dispersion of $-4 ps \cdot nm^{-1} \cdot km^{-1}$ or less more effectively restrains the waveform degradation of the light signal caused by the nonlinear optical phenomena. Accordingly, it is possible to make a larger-volume and longer-distance transmission, using the light signal of numerous wavelengths in wavelength band B.

Also, it is ideal that the effective area of the optical fiber according to the present invention is $40\ \mu m^2$ or more at a wavelength of 1550 nm. In this case, the waveform degradation of the light signal caused by nonlinear optical phenomena becomes below the level of signal deterioration due to nonlinearities in the case of the dispersion-shifted optical fiber that is stipulated in G.653 of ITU, and hence it is suitable for performing a long-haul transmission.

Also, the increase in loss due to the OH group of the optical fiber according to the present invention is preferably $-0.1 dB \cdot km^{-1}$ or less at a

wavelength of 1380 nm. In this case, because a wavelength near the 1380 nm wavelength can also be used as the light signal wavelength, it is possible to make a larger- volume transmission.

A refractive index profile that is suitable for realizing the optical fiber according to the present invention is explained in the following. The refractive index profile shown in Figure 2 has, in the order of enumeration from the center of the optical axis, a central core region (refractive index n_1, outer diameter 2a), a second core region (refractive index n_2, outer diameter 2b), a third core region (refractive index n_3, outer diameter 2c), and a clad region (refractive index n_4). The size relations of the respective refractive indexes are $n_1>n_2$, $n_2 < n_3$, and $n_3 > n_4$. More preferably, the relative refractive index difference Δ_1 of the central core region is from 0.4 % to 0.7 % based on the refractive index of the outermost layer of the clad region. An optical fiber having such a refractive index profile can be obtained by adding on the silica glass basis, for example, GeO_2 to both the central core region and the third core region, and/or F element to both the second core region and the clad region.

The refractive index profile shown in Figure 3 is such that the clad region in the refractive index profile of Figure 2 is replaced by an inner clad region (refractive index n_4, outer diameter 2d) and an outer clad region (refractive index n_5), wherein $n_4 < n_5$. Preferably, the relative refractive index difference Δ_1 of the central core region is from 0.4 % to 0.7 % based on the refractive index of the outermost layer of the outer clad region. An optical fiber having such a refractive index profile can be obtained by adding on the silica

glass basis, for example, GeO_2 to both the central core region and the third core region, and/or F element to both the second core region and the inner clad region.

Next, four implementation examples regarding the optical fiber according to the present invention are explained in reference to Table 1. The optical fibers of the implementation examples have the refractive index profiles shown in Figure 3. Figure 4 is a graph showing the chromatic dispersion characteristics of each of the optical fibers in the implementation examples.

Table 1.

	EXAMPLES			
Example #	1	2	3	4
2a(μm)	5.7	5.5	5.2	5.0
2b(μm)	14.7	14.5	15.1	14.3
2c(μm)	22.5	21.3	21.6	21.6
2d(μm)	45.2	42.6	43.2	43.2
Δn_1(%)	0.50	0.55	0.57	0.59
Δn_2(%)	-0.20	-0.20	-0.20	-0.15
Δn_3(%)	0.25	0.30	0.29	0.27
Δn_4(%)	-0.20	-0.20	-0.20	-0.15
Chromatic dispersion ($ps \cdot nm^{-1} \cdot km^{-1}$)				
at 1250 nm	-11.98	-11.82	-12.60	-16.40
at 1310 nm	-9.22	-8.81	-9.42	-14.30
at 1550 nm	-8.07	-6.28	-7.99	-14.70
at 1650 nm	-3.81	-3.32	-7.10	-8.60
Dispersion slope ($ps \cdot nm^{-2} \cdot km^{-1}$) (1)	0.016	0.011	-0.008	0.027
Effective area (μm^2) (1)	52.1	46.6	42.1	49.3
Mode field diameter (μm) (1)	7.95	7.44	7.15	7.75
Bend loss (dB) (2)	2.4	0.2	1.5	0.8
λ_0(nm)	1694	1700	1757	1724
λ_c (nm)	1290	1310	1220	1330
$\Delta \alpha_{1.38}$($dB \cdot km^{-1}$)	0.01	0.06	0.03	0.03

(1) at 1550 nm

(2) at 1550 nm, 1 turn 32 mm

The chromatic dispersion of each optical fiber in the first through fourth implementation examples is –20 ps·nm^{-1}·km^{-1} or more but –3 ps·nm^{-1}·km^{-1} or less at all wavelengths in the wavelength band A as well as the wavelength band B. Also, each optical fiber in the first through fourth implementation examples has an effective area of 40μm or more at a wavelength of 1550 nm and loss increase of 0.1dB·km^{-1} or less due to OH group at a wavelength of 1380 nm. The chromatic dispersion of each optical fiber in the first through third implementation examples is –12 ps·nm^{-1}·km^{-1} or more but –4 ps·nm^{-1}·km^{-1} or less in all wavelengths in the wavelength band A. Also, the chromatic dispersion of the optical fiber in the third implementation example is –16 ps·nm^{-1}·km^{-1} or more but –4 ps·nm^{-1}·km^{-1} or less at all wavelengths in the wavelength band B.

Next, a first embodiment of an optical transmission system employing the optical fiber according to the present invention as an optical transmission line is explained with reference to Figure 5. An optical transmission system 1 is provided with an optical fiber 130 as the optical transmission line between a transmitting station 110 and a receiving station 120.

The transmitting station 110 includes N units of transmitters 111_1 - 111_N ($N \geqq 2$) and an optical multiplexer 112. The transmitter 111_n (n is an integer of 1 or greater but not greater than N) outputs a light signal having a wavelength of λ_n within the wavelength band A or wavelength band B. Of the wavelengths λ_1 to λ_N, some are in 1.31 μm band, some other wavelengths are in 1.45 μm band, some other wavelengths are in 1.55 μm band and the other wavelengths

are in 1.58 μm band. The optical multiplexer 112 multiplexes the light signals of wavelengths λ_1-λ_N and sends out the same to the optical fiber 130. The optical fiber 130 transmits the multiplexed light signals having wavelengths λ_1-λ_N, which have been sent out by the optical multiplexer 112, to the receiving station 120. The optical fiber 130 exhibits the chromatic dispersions in the range of -20 ps·nm^{-1}·km^{-1} or more but -3 ps·nm^{-1}·km^{-1} or less at all wavelengths in the wavelength band A. Also, the chromatic dispersion of the optical fiber 130 is preferably -12 ps·nm^{-1}·km^{-1} or more but equal to or less than -4 ps·nm^{-1}·km^{-1} at all wavelengths of the wavelength band A, or -20 ps·nm^{-1}·km^{-1} or more but equal to or less than -3 ps·nm^{-1}·km^{-1} at all wavelengths of the wavelength band B. More preferably, the chromatic dispersion is -16 ps·nm^{-1}·km^{-1} or more but -4 ps·nm^{-1}·km^{-1} or less at all wavelengths in the wavelength band B. Also, more preferably, the effective area of the optical fiber 130 is 40 μm^2 or more at a wavelength of 1550 nm, and the loss increase due to OH group at a wavelength of 1380 nm is 0.1 dB·km^{-1} or less.

The receiving station 120 includes N units of receivers 121_1 - 121_N and a demultiplexer 122. The demultiplexer 122 demultiplexes the multiplexed light signals having the wavelengths of λ_1-λ_N, which have been received through the optical fiber 130, and outputs the same. A receiver 121_n receives light signal having a wavelength of λ_n which has been output from the demultiplexer 122.

As for this optical transmission system 1, since the optical fiber 130 according to the present invention as mentioned above is used as the optical

transmission line between the transmitting station 110 and the receiving station 120, the waveform degradation of the light signal due to nonlinear optical phenomena as well as the waveform degradation of the light signal due to the accumulation of the chromatic dispersions are restrained at all wavelengths of the wavelength band A or the wavelength band B, including the 1.31 μm band, 1.45 μm band, 1.55 μm band, and 1.58 μm band. Therefore, the optical transmission system 1 enables a large-volume long-haul transmission using light signals having the numerous wavelengths of λ_1-λ_N in the wavelength band A or the wavelength band B.

Next, a second embodiment of an optical transmission system employing the optical fiber according to the present invention as an optical transmission line is explained with reference to Figure 6. An optical transmission system 2 is provided with an optical fiber 231 as the optical transmission line between a transmitting station 210 and a relay station 240 and further provided with an optical fiber 232 as an optical transmission line between the relay station 240 and a receiving station 220.

The transmitting station 210 includes N units of transmitters 211_1 – 211_N, optical multiplexers 212_1, 212_2, optical amplifiers 213_1, 213_2, and an optical multiplexer 214. The transmitter 211_n outputs a light signal having wavelength λ_n in the wavelength band A or wavelength band B. Of the wavelengths λ_1 - λ_N, some are in 1.31 μm band, some other wavelengths are in 1.45 μm band, some other wavelengths are in 1.55 μm band, and the other wavelengths are in 1.58 μm band. The optical multiplexer 212_1 multiplexes

light signals having wavelengths λ_1-λ_M in a first wavelength band which have been sent out from transmitters 211_1 - 211_M (M is an integer of 1 or greater but not greater than N). The optical amplifier 213_1 amplifies the multiplexed light signals having wavelengths λ_1-λ_M altogether, and outputs the same. The optical multiplexer 212_2 multiplexes light signals having wavelengths λ_{M+1} - λ_N in a second wavelength band which have been sent out from the transmitters 211_{M+1} - 211_N, and the optical amplifier 213_2 amplifies the multiplexed light signals having wavelengths λ_{M+1} - λ_N altogether. The optical multiplexer 214 multiplexes the amplified light signals having wavelengths λ_1 - λ_M and the amplified light signals having wavelengths λ_{M+1} - λ_N, and sends out the same to the optical fiber 231.

The optical fiber 231 transmits the light signals having wavelengths λ_1-λ_N, which have been sent out from the transmitting station 210, to the relay station 240. This optical fiber 231 exhibits the chromatic dispersions of –20 ps·nm^{-1}·km^{-1} or more but –3 ps·nm^{-1}·km^{-1} or less at all wavelengths of the wavelength band A. Preferably, the chromatic dispersion of the optical fiber 231 is –12 ps·nm^{-1}·km^{-1} or more but –4 ps·nm^{-1}·km^{-1} or less at all wavelengths of the wavelength band A, or the chromatic dispersion is –20 ps·nm^{-1}·km^{-1} or more but –3 ps·nm^{-1}·km^{-1} or less at all wavelengths of the wavelength band B. More preferably, the chromatic dispersion is equal to or more than –16 ps·nm^{-1}·km^{-1} but –4 ps·nm^{-1}·km^{-1} or less at all wavelengths in the wavelength band B. Also, the effective area of the optical fiber 231 at the wavelength of 1550 nm is

equal to or more than 40 μm, and the loss increase by OH group at a wavelength of 1380 nm is -0.1 dB·km or less.

The relay station 240 includes a demultiplexer 241, optical amplifiers 242_1, 242_2, and an optical multiplexer 243. The demultiplexer 241 demultiplexes the light signals of wavelengths λ_1 - λ_N that have reached thereto into a first wavelength band including wavelengths λ_1 - λ_M and a second wavelength band including wavelengths λ_{M+1} - λ_N. The optical amplifier 242_1 amplifies the light signals having the wavelengths λ_1 - λ_M in the first wavelength band altogether, and the optical amplifier 242_2 amplifies the light signals having the wavelengths λ_{M+1} - λ_N in the second wavelength band altogether. Then, the optical multiplexer 243 multiplexes the light signals having the wavelengths λ_1 - λ_M and the light signals having wavelength λ_{M+1} - λ_N which have been amplified and output, and sends out the same to an optical fiber 232.

The optical fiber 232 transmits the light signals having wavelength λ_1 - λ_N, which have been sent out from the relay station 240, to the receiving station 220. The optical fiber 232 has the same characteristic as the optical fiber 231.

The receiving station 220 includes N units of receivers 221_1 - 221_N, demultiplexers 222_1, 222_2, optical amplifiers 223_1, 223_2, and a demultiplexer 224. The demultiplexer 224 demultiplexes the light signals having wavelengths λ_1 - λ_N, which have been received through the optical fiber 232, into a first

wavelength band including wavelengths λ_1 - λ_M and a second wavelength band including wavelengths λ_{M+1} - λ_N. The optical amplifier 223_1 amplifies the light signals of wavelengths λ_1 - λ_M altogether, and the demultiplexer 222_1 demultiplexes these light signals of wavelengths λ_1 - λ_M into each wavelength. The optical amplifier 223_2 amplifies the light signals of wavelengths λ_{M+1} - λ_N altogether, and the demultiplexer 222_2 demultiplexes these light signals into each wavelength. The receiver 221_n receives the light signal having the wavelength λ_n which has been output from the demultiplexer 222_1 or 222_2.

As for the optical transmission system 2, since the optical fibers 231, 232 according to the present invention are used, as mentioned above, as the optical transmission lines between the transmitting station 210 and the relay station 240 and between relay station 240 and the receiving station 220, respectively, the waveform degradation of the light signal due to nonlinear optical phenomena as well as the waveform degradation of the light signal due to the accumulation of the chromatic dispersions are restrained at all wavelengths of the wavelength band A or the wavelength band B, including the 1.31 μm band, 1.45 μm band, 1.55 μm band, and 1.58 μm band. Therefore, the optical transmission system 2 enables a large-volume long-haul transmission using light signals having the numerous wavelengths of λ_1 - λ_N in the wavelength band A or the wavelength band B.

Also, in this optical transmission system 2, the optical amplifiers 213_1, 242_1, and 223_1 amplify the light signals having wavelength λ_1 - λ_M in the first

wavelength band altogether, and the optical amplifiers 213_2, 242_2, and 223_2 amplify the light signals having wavelengths λ_{M+1} - λ_N in the second wavelength band altogether, and accordingly this enables a long-haul transmission. By way of example, the first wavelength band includes the 1.55 and 1.58 μm band, and an erbium-doped fiber amplifier (EDFA) can be used as the optical amplifier which amplifies the light signals in the first wavelength band altogether. On the other hand, the second wavelength band includes the 1.31 μm band and 1.45 μm band, and a semiconductor optical amplifier or a Raman amplifier can be used as the optical amplifier which amplifies the light signals in the second wavelength band altogether.

In the composition shown in Figure 6, the light signals are divided into two wavelength bands and each of them is amplified by the respective optical amplifier. However, all of them may be amplified by one optical amplifier, or they may be divided into three or more wavelength bands and each of them may be amplified by a respective optical amplifier. For example, the light signals may be divided into four wavelength bands: the 1.31 μm band, 1.45 μm band, 1.55 μm band, and 1.58 μm band. Then, a praseodymium-doped fiber amplifier (PDFA) can be used for the amplification of the light signal at the 1.31 μm band. A thulium-doped fiber amplifier (TDFA) can be used for the amplification of the light signal at the 1.45 μm band. An EDFA can be used for the amplification of the light signals at the 1.55 μm band and the 1.58 μm band, respectively. For the amplification of any light signal in any of the wavelength bands, a semiconductor optical amplifier or a Raman amplifier can

be used.